Fermi Limit of the Neutrino Flux from Gamma-ray Bursts

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If gamma-ray bursts (GRBs) produce high energy cosmic rays, neutrinos are expected to be generated in GRBs due to photo-pion productions. However we stress that the same process also generates electromagnetic (EM) emission induced by the production of secondary electrons and photons, and that the EM emission is expected to be correlated to the neutrino flux. Using the Fermi observational results on gamma-ray flux from GRBs, the GRB neutrino emission is limited to be below $\approx 20\mathrm{GeV\,m^{-2}}$ per GRB event on average, which is independent of the unknown GRB proton luminosity. This neutrino limit suggests that the full IceCube needs stacking more than 370 GRBs in order to detect one GRB muon neutrino. The Fermi observations of GRBs also imply that the ratio between energy in the accelerated protons and electrons is $f_p \lesssim 10$.

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I. Introduction. The sources of high energy, > 1PeV, cosmic rays (HECRs) are expected to produce high energy neutrinos by pion production. The detection of high energy neutrinos will help to identify the origin of HECRs. Gamma-ray bursts (GRBs) have long been proposed to be one of the strong candidates of extragalactic HECRs[1–3], and was expected to produce high energy neutrinos[5, 6]. Currently the IceCube, operating in the full scale, is the most sensitive TeV-scale neutrino telescope, and is believed to reach the level of GRB neutrino flux. The recent reported flux limits from IceCube in its uncompleted configuration have put stringent constraints on GRB neutrino emission[7–9]. The observations by IceCube in full scale will soon give even more stringent results.

The comparison of the latest non-detection of GRB neutrinos by IceCube and the positive GRB neutrino prediction challenges GRBs being the source of HECRs[9][30]. However, the predicted flux depends on some uncertainties in the GRB model. First, the neutrino flux is proportional to the proton luminosity from the GRB jet L_p, which is unknown in GRB model and regarded as a free parameter. Second, the neutrino flux is proportional to the fraction of proton energy that is converted into pions f_π, which is further dependent on other uncertain parameters, e.g., the bulk Lorentz factor of the jet, Γ, and the radius of the GRB emission regions, $R_{\rm em}$[5, 13]. Given the fiducial values of these parameters one can calculate the GRB neutrino flux, as done by Guetta et al. [14] and IceCube[7–9], but the flux is subjected to the uncertainties. For example, if the ratio between energy in accelerated protons and electrons $f_p \equiv L_p/L_e$ is taken to be $f_p = 10$, the predicted neutrino flux by [9, 15] challenge the current non-detection of neutrinos by the IceCube, but using $f_p = 1$ even the photosphere model of GRBs, which has small $R_{\rm em}$ (hence large f_π), survive the current detection limit[16]. A systematic consideration of the parameter values makes relatively more reasonable prediction[17], but the result still suffers the assumptions of parameters.

Here we investigate the neutrino production in GRBs, and emphasize that the neutrino flux could be related to the electromagnetic (EM) one in the pion production processes. Then we derive a constraint on GRB neutrino flux based on the Fermi observations of GRB EM emission. As shown below, this normalization of GRB neutrino flux to gamma-ray emission suffers much less model uncertainties, in particular, independent of the proton luminosity L_p. Without special mention, we will use in the following the convention $Q_x = Q/10^x$ and cgs units.

II. EM and neutrino correlation. The neutrino emission from GRBs are caused by photopion production. If HECRs are generated in GRB outflows, they can interact with the observed intense photon field and produce charged pions via $p+\gamma \to n+\pi^+$. The charged pions decay via the primary mode, $\pi^+ \to \mu^+ + \nu_\mu$, and muons further decay via $\mu^+ \to e^+ + \nu_e + \bar\nu_\mu$. So the initial neutrino flavor ratio in the source is $\Phi^0_{\nu_e} : \Phi^0_{\nu_\mu} : \Phi^0_{\nu_\tau} = 1:2:0$, but due to neutrino oscillation the flavor ratio observed in distance becomes $\Phi_{\nu_e} : \Phi_{\nu_\mu} : \Phi_{\nu_\tau} \approx 1:1:1$[18]. We can see that final products induced by one charged pion decay are four leptons, each roughly shares the pion energy,

$$E_e \approx \varepsilon_{\nu_e} \approx \varepsilon_{\nu_\mu} \approx \varepsilon_{\nu_\tau} \approx E_\pi/4. \quad (1)$$

The generated secondary high energy electrons may easily convert their energy into gamma-rays by radiation processes. Thus there should be a straightforward relation between the muon neutrino flux and the gamma-ray flux induced by the secondary electrons,

$$F_{\nu_\mu} \approx F_\gamma^{\pi^\pm}. \quad (2)$$

This means that the neutrino flux may be normalized to and then constrained by observed gamma-ray flux, which, as shown later, appears mainly in GeV scale.

The secondary electrons are very energetic and cool rapidly by synchrotron radiation. Let us calculate the synchrotron photon energy. For a flat proton distribution with index $p \approx 2$ ($E_p^2 dn_p/dE_p \propto E_p^{2-p}$), and a

typical GRB photon spectrum with Band-function parameters, $\alpha_\gamma = 1$ and $\beta_\gamma = 2$, the energy distribution of the generated secondary pions is dominated by pions at $E_\pi \gtrsim E_{\pi,b} = 0.2E_{p,b}$, where $E_{p,b}$ is the energy of protons that interact with photons with spectral-break energy ϵ_b at Delta resonance [5], $E_{p,b} = 1.3\times10^{16}\Gamma_{2.5}^2\epsilon_{b,\rm MeV}^{-1}$eV, where $\epsilon_{b,\rm MeV} = \epsilon_b/1$MeV. Given that each pion-decay generated electron carries one fourth of the pion energy, the synchrotron photon spectrum emitted by the secondary electrons is mainly dominated by photons above

$$\epsilon_{\rm syn} \simeq 6(\epsilon_B/\epsilon_e)^{1/2}L_{52}^{1/2}\Delta t^{-1}\epsilon_{b,\rm MeV}^{-2}\mathrm{TeV}, \quad (3)$$

where L is the GRB gamma-ray luminosity, Δt is the variability timescale in GRB light curve, and ϵ_e and ϵ_B are the fractions of jet kinetic energy that are carried by accelerated electrons and magnetic field, respectively. High energy photons may interact with the GRB MeV photons and produce electron/positron pairs, $\gamma\gamma \to e^\pm$. The $\gamma\gamma$ optical depth exceeds unity for photon energy above[19, 20]

$$\epsilon_{\gamma\gamma} \simeq \max(1\Delta t_{-2}\Gamma_{2.5}^6 L_{52}^{-1},\, 0.3\Gamma_{2.5})\mathrm{GeV}. \quad (4)$$

Thus $\epsilon_{\rm syn} \gg \epsilon_{\gamma\gamma}$, i.e., the synchrotron photons emitted by secondary electrons may be easily trapped and converted into electron/positron pairs. This initiates an EM cascade: the pairs emit synchrotron photons; the photons are converted back into pairs; the pairs emit photons again. The photons can escape once their energy decays into below $\epsilon_{\gamma\gamma}$ during the EM cascade. Therefore, the total energy of the pion-decay induced electrons finally show up as a EM cascade emission piled up around $\epsilon_{\gamma\gamma}$, typically $\epsilon_{\gamma\gamma} \sim 0.1$GeV−a few 100's GeV for $\Gamma \sim 100-1000$. This is exactly the energy windows of Fermi/LAT. Therefore, we may expect to constrain GRB neutrino flux by using gamma-ray flux observed by Fermi/LAT.

A. Additional gamma-ray components. It should be noted that the observed gamma-ray flux, F_γ, may be contributed not only by the secondary electrons induced EM cascade emission. Let us write $F_{\nu_\mu} = fF_\gamma$ with $F_\gamma = F_\gamma^{\pi^\pm} + F_\gamma^{\rm add}$ and $f < 1$. The additional contributions to the gamma-ray flux could be several origins. First, there may be leptonic component (F_γ^e), emitted by GRB accelerated electrons, other than secondary electron/positron pairs from hadronic processes. Second, the produced neutral pions in $p\gamma$ interactions also introduce additional gamma-ray component ($F_\gamma^{\pi^0}$), which will be considered in more details in the following.

There is comparable possibility that the $p\gamma$ interactions produce neutral pions, $p+\gamma \to p+\pi^0$. Each neutral pion decays into two photons, $\pi^0 \to \gamma\gamma$, and each photon carries one half of the primary pion energy. Approximately we assume the neutral pions follow the flat energy distribution of the charged pions, thus the energy distribution of the secondary photons from neutral pion decays is dominated by those above

$$\epsilon_{\pi,b} \approx 0.5E_{\pi,b} = 1.3\times10^{15}\Gamma_{2.5}^2\epsilon_{b,\rm MeV}^{-1}\mathrm{eV}. \quad (5)$$

This is well above the $\gamma\gamma$ absorption energy (eq.4), so the pion-decay induced photons should be absorbed and lead to an EM cascade emission. However, for very high energy photons the Klein-Nishina effect will reduce the $\gamma\gamma$ interactions. For photons with energy larger than[19, 20]

$$\epsilon_{\rm esc} = 10^{16}\Delta t_{-2}^{-1}\Gamma_{2.5}^{-2}L_{52}\epsilon_{L,\rm keV}^{-1}\mathrm{eV} \quad (6)$$

the optical depth reduces to below unity and the photons can escape. Here $\epsilon_L = 1\epsilon_{L,\rm keV}$keV is the low energy cutoff of the GRB spectrum, due to, for example, the synchrotron self absorption, which is important typically below keV scale[21]. Thus the photons with energy of $\epsilon_{\pi,b} < \epsilon < \epsilon_{\rm eps}$ are trapped inside the GRB emission region and their energy is transferred into EM cascade emission.

On the other hand, the generation of neutrinos and secondary electrons at high energy ranges suffers from the fast cooling of charged pions and muons. Electrons are generated by muon decays, which are slower than their synchrotron cooling for muon energy higher than $E_{\mu,c} = 3\times10^{16}(\epsilon_e/\epsilon_B)^{1/2}\Gamma_{2.5}^4\Delta t_{-2}L_{52}^{-1/2}$eV[7, 14, 22]. The secondary electrons that dominate the EM cascade emission are mainly produced by charged pions with energy of $E_{\pi,b} < E_\pi < (4/3)E_{\mu,c}$.

For a flat primary proton distribution, the generated secondary pions are also flat in energy distribution, approximately $E_\pi^2 dn_\pi/dE_\pi \propto E_\pi^0$. Assuming in the $p\gamma$ processes, comparable energies are carried by the generated charged and neutral pions, the ratio between the energy of secondary electrons from π^+ decays to that of secondary photons from π^0 decays is $\approx \frac{1}{4}\log(\frac{4}{3}E_{\mu,c}/E_{\pi,b})/\log(\epsilon_{\rm esc}/\epsilon_{\pi,b})$, with the factor 1/4 due to that electrons carry one fourth the energy of primary pions. If the gamma-ray flux is only contributed by EM cascade emission from secondary electrons and photons, and given the relation of eq (2), the f factor is then calculated as

$$f = \frac{F_{\nu_\mu}}{F_\gamma^{\pi^\pm} + F_\gamma^{\pi^0}} \approx \frac{\frac{1}{4}\log(\frac{4}{3}E_{\mu,c}/E_{\pi,b})}{\frac{1}{4}\log(\frac{4}{3}E_{\mu,c}/E_{\pi,b}) + \log(\epsilon_{\rm esc}/\epsilon_{\pi,b})}. \quad (7)$$

Plugging the values of $E_{\mu,c}$, $E_{\pi,b}$, $\epsilon_{\rm esc}$ and $\epsilon_{\pi,b}$ we have $f \approx 0.36$ for typical parameter values. If there are other contributions to the gamma-ray flux, e.g., the leptonic component, it should be that $f < 0.36$.

III. Fermi Limit to neutrino flux. The Fermi Gamma-ray Space Telescope provided a brand new window to GRB observations, especially for the GeV scale. We show here how low the GRB neutrino signal has been constrained to be by Fermi observations of GRB gamma-ray emission.

Fermi satellite has two instruments, Gamma-ray Burst Monitor (GBM), with wide field of view (FOV) and being sensitive to MeV scale emission, and Large Area Telescope (LAT), narrower FOV and sensitive to GeV emission, especially from 0.1 to few 100's GeV. The LAT has detected roughly 8% of the GBM-triggered GRBs that

occurred within the LAT FOV. For these LAT-bright GRBs, the analysis by Zheng et al.[23] has shown (their Table 2) the photon fluence (i.t., time integrated photon flux) of each LAT detected GRB in the 0.1-300GeV range. We then get the average photon flucence for one GRB, $\phi_{\rm bright} = 108 {\rm ph\,m^{-2}}$[31]. Since there is quite few photons detected above few 10's GeV, the photon number in 0.1-10GeV range is practically equal to that in the 0.1-300GeV range. In their recent paper[24] the Fermi team has analyzed the LAT-dark GRBs in roughly 3 years operation, which are the other 92% GBM-triggered GRBs that are in the LAT FOV. The upper limits to the gamma-ray flux in 0.1-10GeV range for each GRB has been listed in their Table 1. We use the upper limits in the last column to calculate the average upper limit of all these LAT-dark events, which is $\phi_{\rm dark} = 34.6 {\rm ph\,m^{-2}}$ (0.1-10GeV range). Let us regard $\phi_{\rm bright}$ as the upper limits to the bright GRBs, then we can calculate the average upper limit to all GRBs, including both bright and dark GRBs, as

$$\phi_{\rm limit} = 8\% \times \phi_{\rm bright} + 92\% \times \phi_{\rm dark} = 40 {\rm ph\,m^{-2}} \quad (8)$$

at 0.1-10GeV energy range. Given the photon fluence, one still need the spectral profile in order to know the energy fluence. Assuming a flat photon spectrum, $\epsilon^2 dn_\gamma/d\epsilon \propto \epsilon^{2-\gamma}$ with $\gamma = 2$, the average limit to the fluence of one GRB is

$$F_{\gamma,\rm limit} = 20 {\rm GeV\,m^{-2}} \quad (9)$$

in 0.1-10GeV range. For softer photon spectrum with $\gamma = 3$, the limit becomes $F_{\gamma,\rm limit} = 8.5 {\rm GeV\,m^{-2}}$, smaller by a factor of 2.3, whereas for harder spectrum with $\gamma = 1.5$, $F_{\gamma,\rm limit} = 75 {\rm GeV\,m^{-2}}$, larger by 3.7. Given the correlation between neutrino flux and gamma-ray flux, the average neutrino fluence per GRB is $F_{\nu_\mu} < f F_{\gamma,\rm limit}$.

IV. Neutrino detection rate. Besides the normalization of neutrino flux, one still need the neutrino spectral form in order to calculate the neutrino detection rate by experiments, like the IceCube. For a GRB spectrum with Band-function parameters α_γ and β_γ, and for a flat proton distribution with $p = 2$, the GRB neutrino spectrum generated by the $p\gamma$ interactions can be approximated as $dn_\nu/d\varepsilon \propto \varepsilon^{-\alpha_\nu}$ at $\varepsilon < \varepsilon_1$, $dn_\nu/d\varepsilon \propto \varepsilon^{-\beta_\nu}$ at $\varepsilon_1 < \varepsilon < \varepsilon_2$, and $dn_\nu/d\varepsilon \propto \varepsilon^{-\gamma_\nu}$ at $\varepsilon_2 < \varepsilon$ (For simplicity hereafter we take $\varepsilon \equiv \varepsilon_{\nu_\mu}$) where the spectral indice are $\alpha_\nu = 3 - \beta_\gamma$, $\beta_\nu = 3 - \alpha_\gamma$, and $\gamma_\nu = \beta_\nu + 2$, and the break energies are $\varepsilon_1 = E_{\pi,b}/4$ and $\varepsilon_2 = E_{\mu,c}/3$. The normalization of the neutrino flux is obtained by, given $F_{\nu_\mu} = f F_\gamma$, the requirement that $\int_0^\infty \varepsilon (dn_\nu/d\varepsilon) d\varepsilon = f F_{\gamma,\rm limit}$. For typical GRB spectrum with $\alpha_\gamma = 1$ and $\beta_\gamma = 2$, we get the specific photon flux at $\varepsilon = \varepsilon_1$ is $dn_\nu/d\varepsilon(\varepsilon = \varepsilon_1) = f F_{\gamma,\rm limit}/\varepsilon_1^2 [(3/2) + \log(\varepsilon_2/\varepsilon_1)]$. Note, the broken power law form is a good approximation to the spectral profile of GRB muon neutrinos resulted from a full numercial calculation with the effect of neutrino mixing, e.g. [25].

The effect area of the IceCube in its 40 strings configuration and averaged over incoming angles can be approximated accurately by a function: $\log(A_{\rm eff}^{\rm IC40}/{\rm cm}^2) = a + b_1 x + b_2 x^2 + b_3 x^3 + b_4 x^4$ where $x = \log(\varepsilon/1{\rm GeV})$, $a = -17.27$, $b_1 = 9.16$, $b_2 = -1.67$, $b_3 = 0.142$ and $b_4 = -0.00466$. The effect area of the full scale IceCube (86 strings) is about 3 times larger, $A_{\rm eff}^{\rm IC86} \approx 3 A_{\rm eff}^{\rm IC40}$[26].

Now the average neutrino number that can be detected in one GRB cann be calculated as $N_{\rm det} = \int_0^\infty A_{\rm eff} (dn_\nu/d\varepsilon) d\varepsilon$. For the neutrino spectrum with $F_{\nu_\mu} < 20 f {\rm GeV\,m^{-2}}$, $\varepsilon_1 = 7 \times 10^{14}$eV and $\varepsilon_2 = 10^{16}$eV, the detection rate by the 40-string configuration is $N_{\rm det}^{\rm IC40} = 2.5 \times 10^{-3} f$ (for $\gamma = 2$) in one GRB, so more than $1/N_{\rm det}^{\rm IC40} = 400/f$ GRBs are needed to stack in order to detect one muon neutrino from GRBs. This GRB number are larger than that analyzed by the IceCube collaboration in ref [9]. More GRBs are needed to be observed for positive detection. For the full scale IceCube with larger effect area, and for $f = 0.36$, one needs to stack at least 370 GRBs to detect one GRB muon neutrino (or > 100 and > 850 GRBs for $\gamma = 1.5$ and 3, respectively).

V. Conclusion and discussion. We show that in the $p\gamma$ processes there is a correlation between the generated EM (electrons and photons) and neutrino fluxes. The EM emission cascades down to typically GeV scale, before escaping from the GRB emission region, thus one can use the Fermi/LAT observations to constrain the GRB neutrino flux, which implies that for the IceCube in its 40 string configuration, one needs $> 400/f$ GRBs to detect one GRB muon neutrino, or > 370 GRBs for the full IceCube (taking typical value $f = 0.36$).

Since the gamma-ray flux can be contributed by leptonic processes, e.g., generated by radiation from GRB accelerated electrons, the LAT observations only give an upper limit to the EM emission from $p\gamma$ interactions, and then an upper limit to the neutrino flux. It should be noticed that it is possible that $f \ll 0.36$.

The derivation of neutrino flux using the EM-neutrino correlation is less dependent on the uncertain parameters in GRB models. For example, unlike the previous calculations of GRB neutrino flux, the calculation here does not need to assume the (non-thermal) proton luminosity in GRBs, L_p, or the ratio f_p. Note that the derivation is not parameter free; the location where EM cascade emission piles up depends on the bulk Lorentz factor Γ (eq. 4). However, observational results usually suggest that $\Gamma \sim 10^2 - 10^3$[19, 27, 28].

GBM detects roughly $\sim 10^3$ GRBs each year. The average limit to the neutrino flux per GRB then suggests that the full IceCube detects $\lesssim 3$ muon neutrinos associated with GRBs each year. This is smaller by order of magnitude than the prediction by [5], who normalizes the neutrino flux to the observed flux of ultrahigh energy, $> 10^{19}$eV, cosmic rays (UHECRs). This may challenge the assumption that GRBs are the origin of the observed UHECRs. Otherwise, the local, within ~ 100 Mpc, HECR production rate may be larger by one order of magnitude than in the distant, earlier Universe, since UHECRs come from within the GZK sphere whereas the neutrinos can reach the Earth from the edge of the Uni-

verse.

Given the neutrino flux, one can constrain the HECR production in GRBs, i.e., the ratio between energy in accelerated protons and electrons. It is derived that the protons of energy $E_{p,b}$ typically loses a fraction $f_{\pi,b} \sim 0.2$ of its energy by $p\gamma$ interactions in GRBs[5], and that the ratio between luminosity in neutrinos and protons is[10]

$$\frac{L_{\nu_\mu}}{L_p} \approx \frac{1}{8} f_{\pi,b} \frac{\log(\frac{4}{3}E_{\mu,c}/E_{\pi,b})}{\log(E_{p,\max}/E_{p,\min})} \sim \frac{1}{8} \times f_{\pi,b} \times \frac{1}{5} \quad (10)$$

Here $E_{\max}$ ($E_{\min}$) is the maximum (minimum) energy of accelerated protons. Thus $L_p \sim 200 L_{\nu_\mu}$. The proton to electron ratio is given by $f_p = L_p/L_{\gamma,\mathrm{MeV}} = (L_p/L_{\nu_\mu})(L_{\nu_\mu}/L_{\gamma,\mathrm{MeV}}) \approx 200(F_{\nu_\mu}/F_{\gamma,\mathrm{MeV}}) < 40(F_{\gamma,\mathrm{MeV}}/10^{-5}\mathrm{erg\,cm^{-2}})^{-1}$. In fact, the wide energy range observations by Fermi may have make a clearer constraint. The Fermi observations show that the ratio between flux in LAT and GBM is typically $L_{\gamma,\mathrm{GeV}}/L_{\gamma,\mathrm{MeV}} \lesssim 0.1$[29]. Noting that $f \approx L_{\nu_\mu}/L_{\gamma,\mathrm{GeV}} < 0.36$, by using $f_p \sim L_p/L_{\gamma,\mathrm{MeV}} = (L_p/L_{\nu_\mu})(L_{\nu_\mu}/L_{\gamma,\mathrm{GeV}})(L_{\gamma,\mathrm{GeV}}/L_{\gamma,\mathrm{MeV}})$, we have

$$f_p \lesssim 7 \frac{L_p}{200 L_{\nu_\mu}} \frac{f}{0.36} \frac{L_{\gamma,\mathrm{GeV}}}{0.1 L_{\gamma,\mathrm{MeV}}}. \quad (11)$$

If the GeV gamma-ray flux is dominated by leptonic component, then $f \ll 0.36$. This indicates that the Fermi limit starts to challenge the use of the fiducial number $f_p = 10$ as in the previous literatures.

There may be some caveats that the Fermi Limit can be avoided in some cases. First, we have used the GeV scale, 0.1-few 100's GeV, flux to constrain the neutrino flux, but it could be that the cutoff photon energy is much larger, e.g., $\epsilon_{\gamma\gamma} \gg 100$ GeV, so the observations in < 100 GeV range do not make sense. Second, if for unknown reasons it happened that the generated secondary electrons, i.e., generated by the charged pion decay or $\gamma\gamma$ pair production, do not radiate at all, the EM-neutrino correlation would not exist.

The calculations here assume that the $p\gamma$ interactions happen in a region of radius $R \approx \Gamma^2 c\Delta t$. There are other GRB models where this assumption may not hold, then one should remind that the neutrino flux is model dependent[15].

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[30] The detailed calculations of the normalization of GRB neutrino flux by [10–12] give lower neutrino flux that is consistent with the non-detection.
[31] Note that there are totally 22 LAT detected GRBs listed in Zheng et al.[23], but we only take the 15 reported by Fermi collaboration and neglect the other 7 discovered by using the special method.